Hollowness Perception with Noise-Reduction Hearing Aids

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Abstract

The efficacy of "noise-reduction" hearing aids in reducing the hollowness perception of one's own voice during vocalization was examined. Binaural Siemens 283 ASP hearing aids were worn by 2 groups of listeners, one with primarily high-frequency loss (Group A) and one with loss in both high- and low-frequencies (Group B). Electroacoustic parameters on the hearing aids were adjusted initially for optimal hearing in the "no-noise reduction" mode by rating the clarity of a discourse passage while following an adaptive forced-choice procedure. Afterwards, subjects compared the effect of the noise-reduction circuitry by vocalizing at 3 different voice levels and scaled the clarity-hollowness of their voices using a 0–100 scale with each noise-reduction mode. Group A subjects did not show a significant change in hollowness perception with noise-reduction circuitry, whereas Group B subjects showed significant reduction of hollowness perception at soft and normal voice levels with noise-reduction circuitry. These results demonstrated that some present-day noise-reduction circuitry can be effective in improving some wearers' perceived voice quality during vocalization.

Key Words: Noise-reduction hearing aid, hollowness, occlusion effect

The efficacy of "noise-reduction" hearing aids has been a topic of much research interest. These hearing aids adaptively change frequency responses as the level of the input signal changes. The rationale is that different listening environments require different frequency responses and different amounts of gain from the hearing aids. In noise, it was suggested that less low-frequency amplification may reduce the likelihood of upward-spread of masking effect (Danaher and Pickett, 1975) resulting in an improvement of speech understanding. Although laboratory tests revealed limited enhancement of speech perception in noise with these devices (Van Tasell et al., 1988; Tyler and Kuk, 1989), some studies have noted improvements in subjective perception (Siegelman and Preves, 1987; Kuk et al., 1989; Kuk et al., 1990). The present investigation examined a potential use of noise-reduction hearing aids, namely reducing the hollowness that a hearing-aid listener often perceives in his or her own voice.

Recently, Kuk (1990) studied the insertion gain of a programmable hearing aid when the users were allowed to adjust the frequency response and overall gain to optimize perceived speech clarity while listening to external speech (listening condition) and to their own voices (speaking condition). Subjects selected the frequency responses that provided the clearest speech (with the least amount of hollowness) for the listening and speaking conditions using a modified simplex procedure (Neuman et al., 1987). The results of the study showed that a majority of subjects preferred less insertion gain from their hearing aids for the speaking condition than for the listening condition. Subjects with primarily high-frequency hearing loss showed a fairly constant difference in insertion gain across the test frequencies, whereas subjects with hearing loss in both the high and low frequencies showed more insertion gain.
difference between the two conditions in the low frequencies (500 Hz and below) than in the high frequencies. It was suggested that hearing aids with multiple frequency responses may be necessary for optimal performance in listening and speaking conditions for subjects with hearing loss in both the low- and high-frequency regions.

An alternative to optimize hearing-aid performance in both listening and speaking conditions will be for the hearing aid to automatically change its frequency response for the two conditions. However, one must be certain that the hearing aid changes its frequency-gain characteristics in the appropriate frequency region by a suitable amount and with the appropriate time constants.

The use of noise-reduction hearing aids may reduce the hollowness of one's voice by lowering low-frequency and overall gain when the wearer speaks. Assume that the hearing-aid wearer speaks at the same intensity level as an average talker. In a quiet listening situation, speech from a talker reaches the hearing aid microphone at approximately 65 dB SPL. This level may be below the activation threshold of a noise-reduction hearing aid. However, if the wearer speaks with the same vocal effort, the sound pressure level reaching the hearing aid microphone could be approximately 10 to 15 dB more intense (Dunn and Farnsworth, 1939) than when the talker speaks. This level is typically intense enough to trigger the activation of the noise-reduction circuit. Once activated, most noise-reduction hearing aids reduce the low-frequency gain by an amount proportional to the input level. Because the perception of hollowness is dependent on the overall gain and low-frequency gain of the hearing aid (Kuk, 1990), a reduction in gain will likely result in an improvement in the perceived quality of one's own voice.

The present study examined the usefulness of noise-reduction hearing aids in enhancing the perceived quality of one's voice during vocalization. Specifically, we asked the following questions. First, do noise-reduction hearing aids enhance a wearer's perception of his or her own voice quality during vocalization when the hearing aids are fitted according to the wearer's preference? Second, will fitting the hearing aids in quiet or in noise affect the outcome of the comparison? Lastly, do the subjects' voice levels affect the effectiveness of the noise-reduction hearing aids?

**METHOD**

**Subjects**

Nineteen experienced hearing-aid users participated. Subjects ranged from 59 to 88 years of age with a mean of 70 years. All subjects had bilaterally symmetrical sensorineural hearing loss.

Subjects were divided into two groups based on their hearing loss at the 250 and 500 Hz regions. The mean hearing loss at these two frequencies was less than 40 dB HL (re: ANSI, 1969) for Group A subjects. The mean hearing loss for Group B subjects at these two frequencies was equal to or greater than 40 dB HL. Ten subjects were assigned to Group A and nine subjects were assigned to Group B. Subjects were assigned to different groups because it was speculated that Group B subjects, by virtue of their hearing loss, need more low-frequency amplification and may show a positive effect with the noise-reduction hearing aids. None of the subjects had worn a noise-reduction hearing aid prior to the experiment nor had they participated in any research studies at this facility previously. Table 1 summarizes the subjects' mean age, years of hearing aid use, and audiometric thresholds in both ears from 250 to 8000 Hz at octave intervals.

<table>
<thead>
<tr>
<th>Table 1 Subject Characteristics</th>
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<td><strong>Audiometric Thresholds (dB HL, Re: ANSI, 1969)</strong></td>
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<td><strong>Frequency (kHz)</strong></td>
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Hearing Aid

The Siemens 283 ASP noise-reduction hearing aid was used because (1) it is a behind-the-ear hearing aid and can be worn by all subjects; and (2) its activation threshold for noise-reduction can be adjusted easily by turning a potentiometer (A-control). The hearing aid has two channels. The low-frequency channel contains a compression circuit for which cut-off frequency can be adjusted from 800 Hz to 1600 Hz (F-control, 8 to 16). Gain in the low-frequency channel can be adjusted over a 20 dB range (G-control, 0 to -20). The combination of the F- and G-controls provides more than 30 dB attenuation below 500 Hz (Fig. 1). The threshold of compression (A-control) can be adjusted also. When the A-control is set to “max,” the compression circuit is activated at 60 dB SPL. When the A-control is set to “min,” the compression threshold is raised so that the hearing aid functions essentially like a linear circuit. The compression circuit has an attack time of 3 msec and a release time of 700 msec. The high-frequency channel is a linear circuit with 48 dB full-on gain and a saturated sound pressure level (SSPL90) of 121 dB SPL.

Test Stimuli

A short discourse passage was used as the stimulus for initial adjustment of the hearing aids to each subject’s comfortable listening level. The passage read:

“In one typical day, New Yorkers threw away enough garbage to provide $120,000 worth of reusable materials.”

This passage was read and recorded in an anechoic chamber by an adult male trained singer. The talker wore a headset that held a Sony ECM-150 electret condenser microphone at a distance of 8 inches from his mouth. The output from the microphone was amplified 40 dB using a Nakamichi FS-100 power supply and a Nakamichi MS-100 microphone mixer. The amplified signal was input to a Sony PCM-501ES digital audio processor, and the passage was recorded on the video channel of a Sony SLHF300 Beta stereo cassette recorder. The passage was subsequently digitized at a rate of 20 kHz with a 12-bit A/D converter, edited using custom software, and stored on the hard drive of an AST computer that was used to control the stimuli. The passage was 8.8 seconds in length and was low-pass filtered at 9000 Hz through a Krohn-Hite (3323R) filter.

Procedures

Subjects were seen on two sessions that were separated by at least 1 week. A different listening condition (i.e., quiet or noise) was used in each session to determine preferred insertion gain. Subjects in each group were tested following an interleaved schedule (i.e., quiet, noise, quiet, and so on) to avoid potential order effect. During each session, the experimenters first adjusted the hearing aids so that they amplified to a comfortable listening level for the subjects. Afterwards, subjects vocalized and scaled the hollowness of the voice while wearing the hearing aids. The insertion gain associated with specific parametric settings was determined at the end of each session.

Hearing Aid Fitting

The Siemens 283 ASP hearing aids were worn binaurally. Custom lucite skeleton earmolds with a Select-A-Vent (SAV) were used. Group A subjects (primarily high-frequency loss) used a 3-mm vent plug with the earmold, whereas Group B subjects used a 1.5-mm vent plug. The lengths of the earmolds varied among subjects because of individual differences. Vents were used to approximate real-life fitting of hearing aids for these subjects. Cox and Alexander (1983), and Kuk (1991) reported that vents improved subjective quality judgment of hearing aids in wearers with mild to moderate degree of hearing loss.

The SSPL90 on the hearing aids was set to just below the subjects’ binaural loudness discomfort level (LDL). This value was obtained

![Figure 1](image-url)

**Figure 1** Two-cc coupler full-on gain curves for the experimental hearing aid at 60 dB SPL input with noise-reduction circuit off (A-control = min). Upper curve (1) was obtained at (F = 0, G = 0, or maximum lows). Lower curve (2) was obtained at (F = 16, G = -20, or minimum lows).
using Hawkins et al's (1987) instructions and with the sinusoidal stimuli presented through the subjects' own earmolds (vent was plugged). The A-control on the hearing aids was set to minimum during LDL determination.

The parameters on the hearing aids (i.e., F- and G-controls) were adjusted for optimal speech clarity while listening in quiet and noisy backgrounds using an individualized, adaptive, forced-choice procedure. Individualized procedure allows subjects to select the optimal setting on the hearing aids according to their preference.

Subjects sat in an Industrial Acoustics Company (IAC) sound-treated booth while the hearing aids were being adjusted. The discourse passage was presented at 0° azimuth 1 meter from the subject. The level of the stimulus was 65 dB SPL measured at the subject's position. A 65 dB SPL multitalker babble noise was mixed with the speech stimulus when the fitting procedure was carried out in noise.

All subjects wore the hearing aids at the same F- and G-control settings (F = 12, G = -15) initially. Subjects listened to the discourse passage and adjusted the volume on the hearing aids so that the passage was at a most comfortable listening (MCL) level. Afterwards, the experimenter instructed the subjects to listen and compare the sound quality of the hearing aids at two G-control settings i.e., (F = 12, G = -5) and (F = 12, G = -15). Subjects were instructed to indicate which hearing aid setting yielded the clearest speech. If subjects preferred more low-frequency gain (i.e., G = -5 was preferred over G = -15), the next comparison would be for more low-frequency gain (i.e., G = -5 and G = 0). If, in this comparison the subject preferred less low-frequency gain (i.e., G = 5 and G = -15), the next comparison would be between G = -5 and G = -15. A change in the direction of comparison is termed a reversal. The nominal difference in gain between parametric settings was halved after every reversal. Comparison was terminated after three reversals were encountered, and the final F- and G-control settings were recorded.

When the G-control was adjusted to either extreme (i.e., G = 0 or G = -20), the optimization procedure was repeated to determine the optimal F-control setting while the G-control setting was fixed at the previously determined level. This procedure was repeated twice, and the average setting was recorded for the specific listening condition (i.e., quiet and noise). Subjects were not allowed to vocalize during this fitting procedure because of potential biases to the preferred gain setting (Kuk, 1990). All communications between the experimenter and the subjects were by gesture or by writing. The instructions to the subjects can be found in Appendix A.

**Subjective Scaling Task**

Subjects sat in a carpeted office room (9.5' x 8.0' x 7.5') with the fitted hearing aids (at fixed volume setting) and were asked to rate the clarity/hollowness of their own vocalization. The ambient noise floor of the room was less than 55 dB SPL overall. To facilitate comparison across subjects and to ensure maximum observable effect, all subjects were asked to repeat the phrase “Baby Jeanie was teeny tiny” while wearing the hearing aids. This phrase was used because of the abundance of /i/s which has the lowest F1 formant to demonstrate low-frequency effect (Killion et al, 1988).

Subjects judged their voice quality at 3 voice levels. Subjects read at a normal conversational level first, followed by a loud conversational level and then a soft conversational level. At each voice level subjects repeated the phrase 4 times before indicating their response. Subjects assigned numbers between 0 and 100 to reflect the hollowness/clarity of their voice while repeating the phrase. A “0” was assigned if the voice was extremely hollow, and a “100” was assigned if the voice was extremely clear with no hollowness. At each voice level, the hearing aids were set to noise-reduction on (A-control = max) and noise-reduction off (A-control = min), each for 5 times and in random order.

Sound level meters were placed at 16 inches in front of the subjects' mouth (Quest) and at ear level (Brüel & Kjær) in order to measure the subjects' voice levels. Subjects were instructed to maintain their voice at a consistent level for all words in the phrase by attending to the VU reading on the sound level meter that was placed directly in front of them. The instructions given to the subjects can be found in Appendix B.

An Acoustimed HA-2000 probe microphone system was used to determine the insertion gain provided by the hearing aids fitted in quiet and in noise. Subjects sat approximately 2 feet from the loudspeaker, which was placed at 45° azimuth to the side of the aided ear. The probe tube was inserted to, and visually inspected to be about 3 to 5 mm from the eardrum. A speech-shaped complex noise presented at 65 dB SPL was used as the stimulus. Subjects were in-
structured to refrain from any movements. The hearing aid was set to minimum noise-reduction (i.e., A-control = min). Each insertion gain curve was determined twice and the average curve was reported.

**RESULTS**

**Preferred Insertion Gain for Quiet and Noise**

The preferred insertion gain curves selected by both groups of subjects are summarized in Figure 2. As expected, more insertion gain in the 250 to 1000 Hz regions was selected by Group B subjects (hearing loss in both the low- and high-frequency regions) than Group A subjects (hearing loss primarily in the high-frequency region). Preferred insertion gain above 2000 Hz was similar for both groups.

It was evident that the mean preferred insertion gain determined with the discourse stimuli presented in quiet was higher than the mean preferred insertion gain determined in the presence of noise by approximately 2 to 3 dB across frequencies. This difference, however, was not statistically significant.

**Effect of Noise-Reduction Circuit on Hollowness Perception**

Non-parametric statistics were used for data analysis because such methods make no assumption on the distribution of the responses nor do they require the data to be in either ratio or interval scales. However, the use of non-parametric statistics means that the effect of noise-reduction circuitry on hollowness perception must be studied for each group by voice level by fitting method separately.

A Wilcoxon Matched-Pairs Signed-Rank test was used to examine the significance of the noise-reduction circuitry on changing hollowness perception for each subject group (2) by voice level (3) by fitting method (2) condition (12). To do this, individual hollowness ratings for noise-reduction ‘on’ and ‘off’ conditions were first converted into ranks. The mean rank for each of the noise-reduction conditions was calculated for each subject and the difference in mean rank between the noise-reduction ‘on’ and ‘off’ conditions was analyzed for all 12 experimental conditions. Of all the 12 subject group x voice level x fitting method conditions, only the conditions where group B subjects (with hearing loss in both high and low frequencies), wearing the hearing aids fitted in quiet reached significance at the soft and normal conversational voice levels (Z = 2.2 and 2.1 for soft and normal conversational levels respectively, p < .05). The effect of noise-reduction circuitry was statistically nonsignificant for the other conditions.

Change in hollowness perception was also examined on an individual basis. Individual subject responses (i.e., hollowness ratings) were rank ordered, and a Mann-Whitney U Test was performed on each individual subject for each of the fitting methods and voice level combinations. Figure 3 summarizes the proportion of subjects who showed a statistically significant (p < .05) positive effect (i.e., less hollowness with noise reduction ‘on’), a positive, but non-significant effect (i.e., p > .05) and a negative, but nonsignificant effect (i.e., p > .05). Not one subject showed a significant negative effect (i.e., more hollowness with noise reduction ‘on’).

Figures 3A and 3B showed that only 20 percent of Group A subjects (2/10) showed a significant positive noise-reduction effect when speaking at a soft or normal conversational level regardless of how the hearing aids were fitted. At these levels, approximately 60 percent to 70 percent of Group A subjects showed a positive effect. At a loud conversational level, only half of Group A subjects showed a nonsignificant positive reaction to the action of the noise-reduction circuitry. As indicated earlier, these changes were statistically nonsignificant.

Figures 3C and 3D showed that Group B subjects responded differently to the noise-reduction circuitry than Group A subjects. At a soft level, all subjects (except one subject with the hearing aids fitted in noise) showed a reduction in hollowness perception with the activation of the noise-reduction circuit. As indicated earlier, these changes were statistically nonsignificant.

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The present experiment shows that noise-reduction hearing aids can improve the self-perceived voice quality of the wearer's own voice. For individuals with at least a moderate degree of hearing loss in both high- and low-frequencies (250 to 500 Hz), the effect was more evident when the individual speaks at a soft to normal voice level (about 70 to 75 dB SPL measured at the ear level). For individuals with primarily high-frequency hearing loss, such an effect may not be noticeable.

The results agree well with the experimental hypothesis. Group B subjects, by virtue of their hearing loss, generally preferred more low-frequency insertion gain than Group A subjects when the hearing aids were adjusted in the minimum noise-reduction condition. When the hearing aids were switched to maximum noise-reduction, subjects with more low-frequency insertion gain (i.e., Group B) noticed more difference between maximum and minimum noise-reduction states than subjects with less low-frequency insertion gain (i.e., Group A). This is the case when subjects vocalized at a soft-to-normal voice level. At a loud voice level, the hearing aids might have been saturated to obscure any discriminable effects due to the noise-reduction circuit.

Some studies have suggested that noise-reduction hearing aids may improve the subjective quality of the processed speech in noisy situations (Siegelman and Preves, 1987; Kuk et al, 1990). The present study adds a new use for such hearing aids: that of improving the perception of one's own voice during vocalization. This is an important use for noise-reduction hearing aids in that the perception of hollowness is a major reason for patient dissatisfaction with their hearing aids (Zelnick, 1987). Noise-reduction hearing aids, or more appropriately, hearing aids with adaptive frequency responses, when used in conjunction with appropriate venting, may be the hearing aid of choice for individuals with hearing loss in both high- and low-frequency regions.

The results of the present experiment may be limited to the particular noise-reduction hearing aid used. Different noise-reduction hearing aids use different noise-reduction algorithms and attenuate the low-frequency region by different amounts. Obviously, the effectiveness of a particular hearing aid circuit in reducing hollowness perception depends on the match between the action of the adaptive frequency response system, (i.e., when is the circuit acti-
findings. First, noise-reduction hearing aids use of adaptive frequency response hearing aids design considerations are necessary for optimal preferred by the hearing-aid wearer. Careful what frequency regions are affected), and that activated, how much attenuation is provided, and that noise-reduction hearing aids will not benefit individuals with primarily high-frequency hearing loss. The noted noise-reduction effect is probably related to the amount of preferred low-frequency insertion gain, the voice level, and ultimately the real-ear SPL in the ear canal. If a Group A subject (high-frequency loss) prefers more low-frequency gain, it is likely that the subject could also notice a reduction of hollowness perception with noise-reduction hearing aids.

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REFERENCES

APPENDIX A:
INSTRUCTION TO SUBJECTS FOR FORCED-CHOICE PROCEDURE

"I am going to adjust your hearing aids so that they sound comfortably loud and clear for you. First, you will adjust the volume on the hearing aids up and down until the short passage is at a most comfortable listening level. By that I mean it is not too loud nor too soft, a level that you can listen to for a long period of time without undue stress. I will then adjust the hearing aids and I will call that number 1. You will listen to the passage again and try to remember how many 1 sounds. Afterwards, I will adjust the hearing aids to a different setting. I will call it number 2. Your task is to compare the quality of sound processed by hearing aid numbers 1 and 2. I want you to indicate to me which hearing aid sounds clearer. Raise one finger if number one sounded clearer and raise two fingers if number two sounded clearer. If you would like me to repeat your choice, draw a circle with your finger in the air. You must pick one of the two hearing aids even if you do not like either one or if you cannot tell much difference between them. I want you to base your judgment on the quality of sound. If there is a noticeable difference in the volume of sounds, please let me know so that I can readjust the volume."

APPENDIX B: INSTRUCTIONS FOR SUBJECTIVE SCALING

"You will say 'Baby Jeanie was teeny tiny' at three different voice levels—a normal voice level, a loud voice level, and a soft voice level. At each voice level, you will repeat the phrase 4 times while monitoring the level of your voice on the VU meter. While you are repeating the phrase, I want you to pay attention to the amount of hollowness in your own voice. That is, how much you sound like you’re talking through a tunnel. If your voice is extremely hollow, I want you to assign a number 0. If your voice is extremely clear, I want you to assign a number 100. Assign numbers between 0 and 100 if the hollowness of your voice is between these two extremes. We will begin at a normal conversational level. After we have done this 10 times, we will move to a loud volume and finally to a soft volume. Do you have any questions?"